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Design of an Enhanced Electric Field Sensor Circuit in 0.18 μm CMOS for a Lab-on-a-Chip Bio-cell Detection Micro-Array

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Abstract: An improved CMOS Electric-Field Sensor circuit for sensing bio-cells is presented. The sensor can be used in a Lab-on-a-chip micro-array that uses dielectrophoretic actuation for detecting bio-cells. Compared to the previously published design (DeFET), this improved circuit utilizes the current in both branches of the DeFET to provide a much larger output sensed voltage for the same input electric field intensity (V/m). The enhanced circuit indicates several orders higher electric field sensitivity based on the same 0.18 μm CMOS technology. In general, the improved circuit is found to provide 30dB higher sensitivity relative to the previous DeFET circuit. *Copyright © 2008 IFSA.*

Keywords: Electric-field sensor, Dielectrophoresis, Bio-cells, Lab-on-a-chip

1. Introduction

Biological analysis at a miniaturized scale leading to Lab-on-a-chip [1], [4] is an area of immense current research focus in the emerging field of micro-bioelectronics and micro-biotechnology. Sensing and sorting the presence of biological cells and/or organic macro-molecules is an important aspect of today's efforts in miniaturized biotechnological devices and monolithic systems. There are many existing techniques for determining the presence and concentration of cells or bio-macromolecules e.g., MEMS devices, ultra-sound, magnetic sorting and dielectrophoresis [5]. Dielectrophoretic levitation technique [1], [3], [4] using a non-uniform electric field has recently gained considerable attention in Lab-on-a-chip applications, particularly for biological elements which are less than 1 μm in diameter such as virus, bacteria and protein molecules. These microbes and sub-microbes being very susceptible to contamination and membrane rupture are well suited to dielectrophoretic detection techniques. For dielectrophoretic actuation [1], an applied non-uniform electric field creates a dipole on the biocell and forces the biocell dipoles to concentrate either towards the region of lower electric field concentration (negative dielectrophoresis) if the cell has lower dielectric polarizability compared to the surrounding medium or towards the region of higher electric field concentration (positive dielectrophoresis) if the cell has higher dielectric polarizability compared to the surrounding medium. The sensing part of dielectrophoretic analysis has been carried out mostly using either the optical technique [6] or the impedance sensing technique [7]. However, there is a more direct method of sensing in dielectrophoretic analysis which involves the detection of the change in the original applied electric field concentration due to the presence and the concentration distribution of the bio-cells. The authors in [1], [2] describes a suitable CMOS differential electric field sensitive Field Effect Transistor (DeFET) device for detecting changes in the gradient of the non-uniform electric field in any particular location (spot) in a single-chip miniaturized Lab-on-a-chip system. In this paper, the DeFET design presented in [1] and [2] is considerably improved which is called an enhanced DeFET (EDeFET) circuit where the currents in both the branches of the DeFET device are utilized to provide higher sensitivity. Preliminary work on this proposed circuit was reported in [8].

2. Enhanced DeFET Circuit

Fig. 1 shows the originally proposed CMOS DeFET circuit [1], [2] which consists of non-uniform electric field being applied across the inputs Vin1 and Vin2. The difference between Vin1 and Vin2 reflects the intensity of the electric field. Vin1 and Vin2 connect to two sets of cross-coupled complementary devices. This connection causes the overdrives of both the PMOS and NMOS devices of one branch to go up as the overdrives of both the PMOS and NMOS devices of the other branch goes down. The applied electric field (using a set of electrodes) can be considered as a bias electric field which keeps all the PMOS and NMOS channels ON preferably in the saturation region (for sensing linearity). Changing electric field intensity will cause Vin1 and Vin2 to move in opposite directions (one increasing and one decreasing). As a result, current in the branch M1and M4 will go up when the current in the branch M2and M3 goes down and vice versa. Consequently, this widening differential current between the two branches can be exploited to detect small variations in the electric field intensity. However, in the original circuit this differential current is not exploited to obtain a higher possible sensitivity to electric field intensity variations.

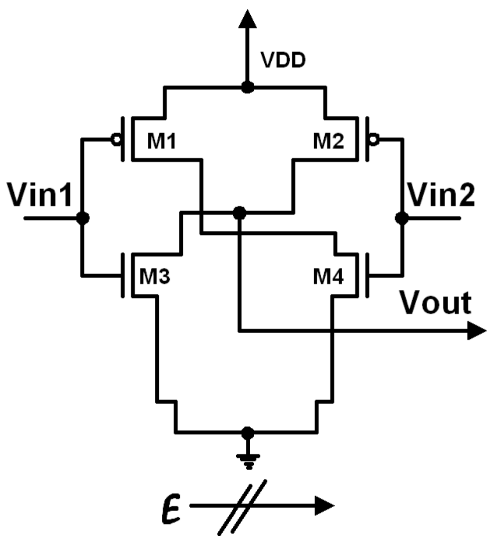

Fig. 1. A CMOS differential electric field sensitive field effect transistor (DeFET) for non-uniform electric field sensing.

Fig. 2 shows the CMOS Enhanced DeFET (EDeFET) circuit where two current mirrors are used to copy the currents in the two branches of the DeFET, which are then combined differentially at the input (Voi) of an inverter amplifier. The output of this inverter (Vout) is the final output of this EDeFET circuit. M5, M7, M9, M10, M6 and M8 forms the current mirrors which differentially combines the two branch currents of the DeFET formed by M1, M2, M3 and M4.

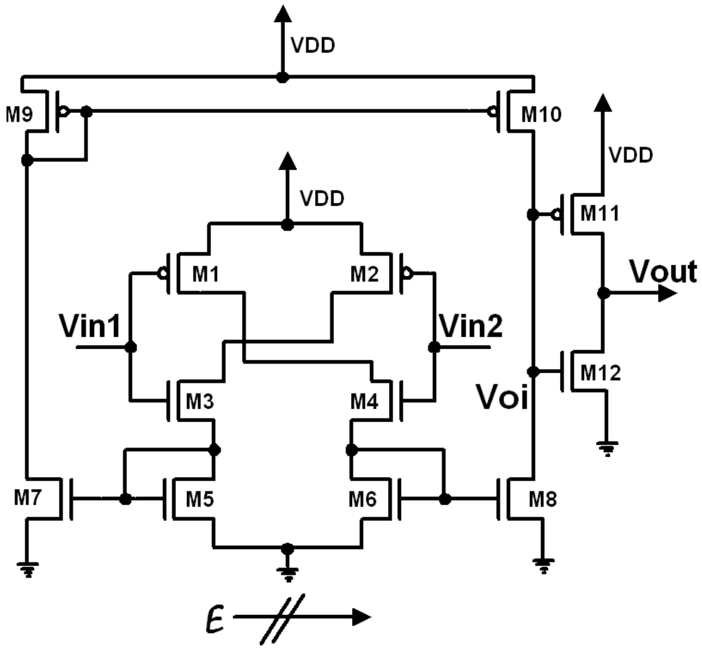

Fig. 2. A CMOS enhanced differential electric field sensitive field effect transistor (EDeFET) circuit for non-uniform electric field sensing.

As a result of this differential combination of the branch currents at the input of the inverter amplifier, the voltage at the input of the inverter amplifier moves up and down using two mechanisms, an increasing pullup current from M10 and a decreasing pulldown current from M8 (while moving up), and, a decreasing pullup current from M10 and an increasing pulldown current from M8 (while moving down). Consequently there is a large change in the overdrives of M11 and M12 with small changes in the difference between Vin1 and Vin2 (due to the change in the non-uniform electric field). The voltage at the inverter amplifier output (Vout) achieves a considerably larger output swing indicating changes in the electric field intensity compared to the output of the original DeFET derived from only one branch (as clearly evident in Fig. 1). The sensitivity (S_E) of the proposed enhanced electric field sensor, EDeFET is given by

$$S_E = \frac{dV_{out}}{dE} \tag{1}$$

or

$$S_E = \frac{dV_{out}}{dV_{oi}} \frac{dV_{oi}}{dE} \tag{2}$$

or

$$S_E = -A\frac{dV_{oi}}{dE}, \tag{3}$$

where, -A is the gain of the inverter amplifier. Also, the non-uniform electric field intensity, E across the input terminals (separated by displacement X) is related to the differential input voltage by,

$$(V_{in1} - V_{in2}) = \Delta_{vin} = -EX \tag{4}$$

Next, from (1),

$$V_{out} = \int S_E dE \tag{5}$$

or by integrating equation (5), we have,

$$V_{out} = S_E * E + \text{Constant}, \tag{6}$$

when E=0, $\Delta_{vin} = 0$ and V_{out}=V_{outb} where V_{outb} is the bias output voltage at the output of the inverter amplifier. The value of the constant of integration in equation (6), found using this boundary condition, is thus V_{outb}.

Hence,

$$V_{out} = S_E * E + V_{outb} \tag{7}$$

Next, from equation (3)

$$S_E = -A\frac{d(i_{d10} - i_{d8}) * r_{08}//r_{011}}{dE} \tag{8}$$

or

$$S_E = -A * r_{08}//r_{011}\frac{d(i_{d2} - i_{d1})}{dE} \tag{9}$$

or

$$S_E = -A * r_{08}//r_{011}\frac{d(i_{d2} - i_{d1})}{d\Delta_{vin}}\frac{d\Delta_{Vin}}{dE} \tag{10}$$

or, using equation (4),

$$S_E = A * r_{08}//r_{011}\frac{(di_{d2} - di_{d1})}{d\Delta_{vin}} * X \tag{11}$$

or,

$$S_E = A * r_{08} // r_{011} \frac{(g_{m2} d\Delta_{vin2} - g_{m1} d\Delta_{vin1})}{d\Delta_{vin}} * X \tag{12}$$

Assuming M1 and M2 are matched devices (with $g_{m2}=g_{m1}=g_m$), and considering the fact that Vin1 and Vin2 moves in the opposite direction with changes in the non-uniform electric field we have,

$$S_E = A * r_{08} // r_{011} * g_m * \frac{d(\Delta_{vin2} + \Delta_{vin1})}{d\Delta_{vin}} * X \tag{13}$$

or

$$S_E = A * r_{08} // r_{011} * g_m * \frac{d\Delta_{vin}}{d\Delta_{vin}} * X \tag{14}$$

or

$$S_E = A * r_{08} // r_{011} * g_m * X \tag{15}$$

Hence, applying equation (15) into equation (7) we have,

$$V_{out} = A * r_{08} // r_{011} * g_m * X * E + V_{outb} \tag{16}$$

In the originally proposed circuit in Fig. 1, the sensed output voltage,

$$V_{out} = r_{o3} // r_{o2} * (g_{m2} - g_{m3}) * X * E + V_{outb} \tag{17}$$

This equation follows from the fact that in Fig. 1, i_{d2} and i_{d3} are both increasing or decreasing at the same time with change in the electric field, since currents in the PMOS M2 and the NMOS M3 will move in the same direction (both up or both down) as Vin1 and Vin2 moves in the opposite direction due to change in the non-uniform electric field. The advantage of the new enhanced circuit compared to the previous DeFET is thus clearly evident.

Fig. 3 shows a Lab-on-a-chip architecture with all the components, e.g., dielectrophoretic actuation controller (a finite state machine), clocking and power supply, and, signal conditioning circuitry. The enhanced DeFET sensor is located between electrodes in an interleaved pattern on the chip surface. All the signal conditioning circuitry is fabricated underneath the surface dielectrophoretic levitation chamber on the same silicon chip. Top layer metal (e.g., metal 6 in the TSMC 0.18 μm CMOS process) can be used for the electrodes and the gate contacts of the EDeFET sensor circuit.

3. Simulation Results

In order to verify the improved performance of the CMOS EDeFET circuit extensive SPICE simulations were carried out using the TSMC 0.18 μm CMOS process parameters. Fig. 4 shows a 400 μV 5 MHz sinusoidal differential voltage between the inputs of the electric-field sensor due to a sinusoidally varying non-uniform electric field across the input terminals. Fig. 5 shows a 400 mV sinusoidal voltage change at the output of the CMOS EDeFET due to the sensed input of Fig. 4. A 60 dB sensor gain has thus been achieved using the EDeFET circuit. Whereas, Fig. 6 shows a barely 12 mV sinusoidal voltage change at the output of the original DeFET due to the sensed input of Fig. 4.

This corresponds to a barely 30 dB sensor gain. The performance enhancement by the EDeFET circuit by way of around 30 dB higher sensitivity relative to DeFET circuit is thus clearly evident. Fig. 7 shows the gain bandwidth behavior of the EDeFET indicating a flat frequency response with around 58 dB gain until reaching a -3 dB frequency of around 10 MHz which ensures frequency-independent sensing over a wide range of time varying non-uniform electric field. Next, Fig. 8 shows an arbitrarily varying voltage difference (0-50 µV) between the sensor input devices due to arbitrary variations in an applied electric field. Finally, Fig. 9 shows the voltage change at the output of the CMOS EDeFET (0 – 110 mV) due to the sensed arbitrary input voltage change of Fig. 8. Again, in general a gain of over 60 dB is indicated by the EDeFET circuit.

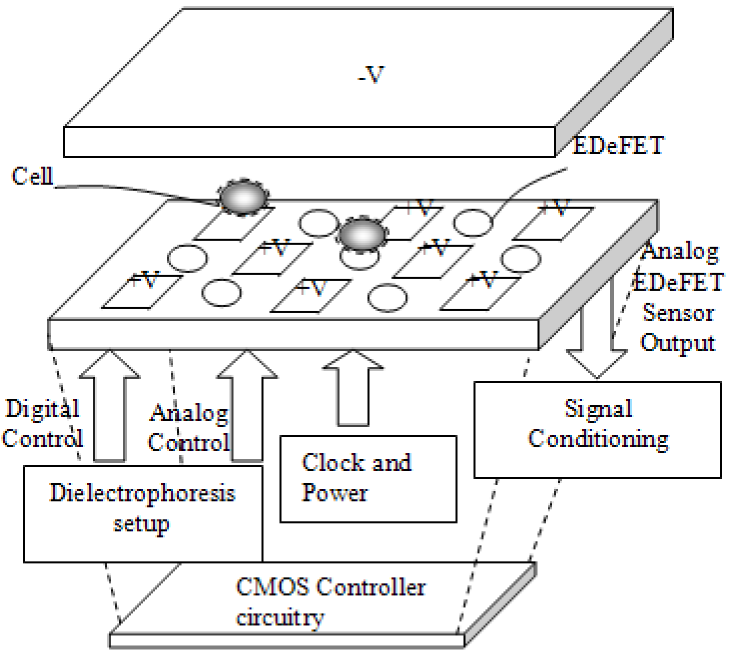

Fig. 3. Lab-on-a-chip system showing all the components and the EDeFET located between electrodes.

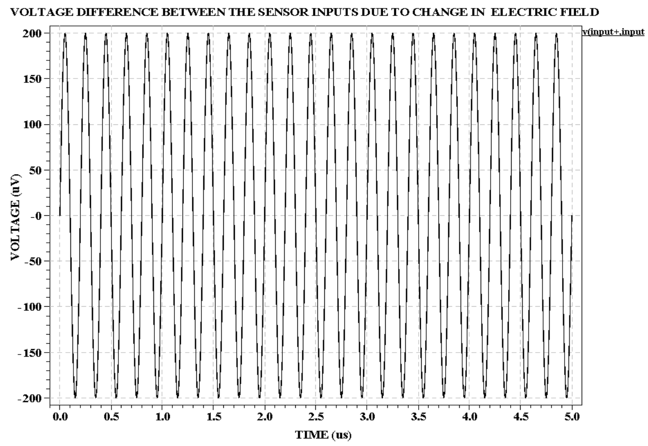

Fig. 4. A 400 µV 5 MHz sinusoidally varying voltage difference between the sensor input devices due to sinusoidal variations in an applied electric field.

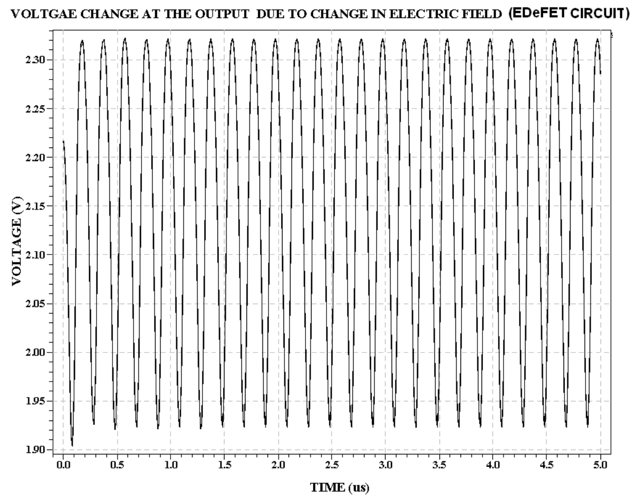

Fig. 5. A 400 mV sinusoidal voltage change at the output of the CMOS EDeFET due to the sensed input of Fig. 4 (A 60 dB sensor gain).

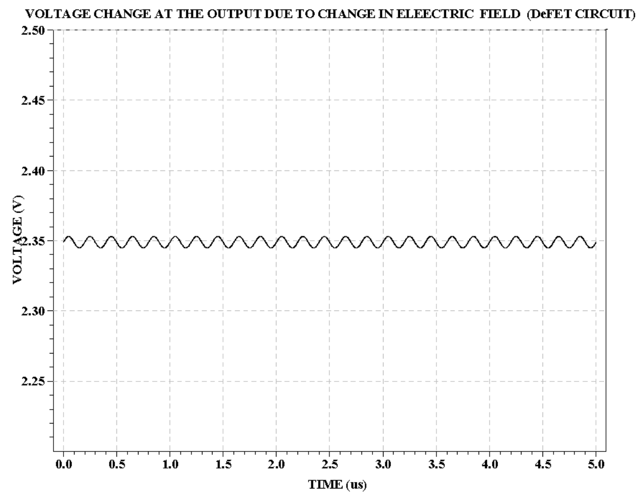

Fig. 6. A 12 mV sinusoidal voltage change at the output of the original DeFET due to the sensed input of Fig. 4 (A 30 dB sensor gain achieved).

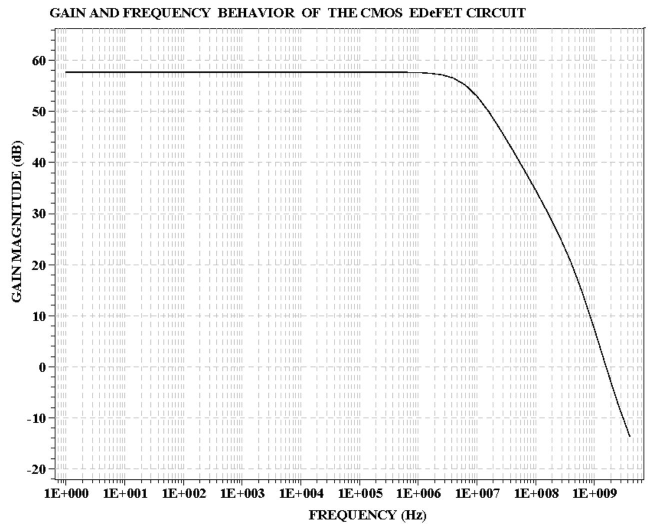

Fig. 7. A 10 MHz -3 dB bandwidth of the CMOS EDeFET circuit.

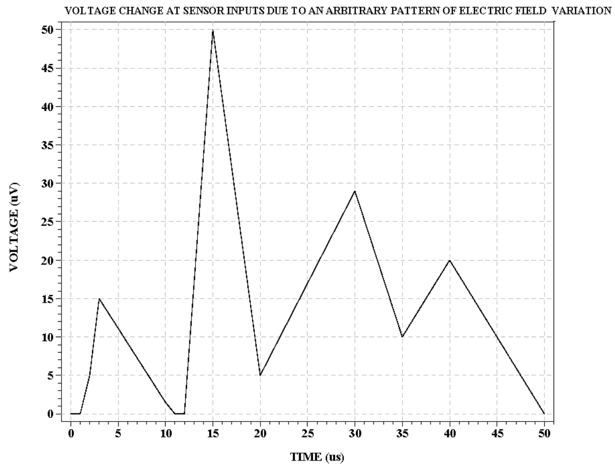

Fig. 8. An arbitrarily varying voltage difference (0-50 μV) between the sensor input devices due to arbitrary variations in an applied electric field.

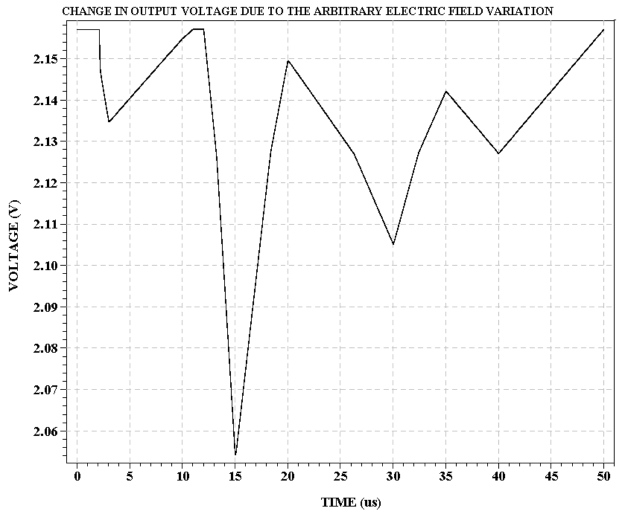

Fig. 9. The voltage change at the output of the CMOS EDeFET (0 - 110 mV) due to the sensed arbitrary input voltage change of Fig. 8.

4. Conclusion

A thorough sensitivity analysis and simulation results for an improved circuit for electric field sensor has been presented. Using the difference of the diverging currents in two branches of DeFET the EDeFET circuit has been developed, providing as much as 30 dB higher sensitivity to non-uniform electric fields. It is extremely suitable for direct sensing of dielectrophoretically levitated cages of biocells.

References

[1]. Y. H. Ghallab and W. Badawy, A novel CMOS lab-on-a-chip for biomedical applications, *Proceedings IEEE ISCAS'2005*, 2005, pp. 1346-1349.
[2]. Y. H. Ghallab and W. Badawy, DeFET: A novel CMOS electric-field sensor for lab-on-a-chip and biomedical applications, *IEEE Sensors Journal,* Vol. 6, 4, 2006, pp. 1027-1037.

[3]. W. M. Arnold, Positioning and levitation media for the separation of biological cells, *IEEE Transactions on Industry Applications,* Vol. 37, 5, 2001, pp. 1468-1475.

[4]. Y. H. Ghallab and W. Badawy, Techniques for biocells sensing, detection and characterization, *Proceedings 2005 International Conference on MEMS, NANO and Smart Systems, ICMENS'05,* CD proceedings, 2005.

[5]. H. A. Pohl, Dielectrophoresis, *Cambridge University Press*, Cambridge, 1978.

[6]. M. S. Talary and R. Pethig, Optical technique for measuring the positive and negative dielectrophoretic behavior of cells and colloidal suspensions, *Proceedings Inst. Elect. Eng. - Sci. Meas. Technol.,* Vol. 14, 5, 1994, pp. 395-399.

[7]. L. L. Sohn, O. A. Saleh, G. R. Facer, A. J. Beavis, R. S. Allan, and D. A. Notterman, Capacitance cytometry: measuring biological cells one by one, *Proceedings Nat. Acad. Sciences, USA,* Vol. 97, 20, 2000, pp. 10687-10690.

[8]. S. M. Rezaul Hasan and Siti Noorjannah Ibrahim, An enhanced CMOS electric field sensor circuit for cells sensing lab-on-a-chip application, *Proceedings International conference on sensing technology(ICST),* Palmerston North, 2007, pp. 255-259.

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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